UTILIZING SURFACE DRILLING DATA TO GENERATE GEOMECHANICAL VALUES FOR USE IN DRILLING AND STIMULATION DESIGN

By

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UTILIZING SURFACE DRILLING DATA TO

GENERATE GEOMECHANICAL VALUES FOR USE

IN DRILLING AND STIMULATION DESIGN

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Abstract:

Geomechanical properties are important for reservoir characterization, drilling operations and optimal stimulation design in the oil and gas industry**.** The conventional techniques to obtain rock mechanical data involve core analysis and/or downhole acoustic/wire-line logging equipment and operations. These techniques can be expensive and sometimes uncertain to process for unconventional reservoirs. In this study, a convenient and cost-effective technique is presented that uses routinely available drilling data to calculate geomechanical properties without the need for downhole logging operations. The calculated rock property logs are compared to test values obtained from log and core values in a similar geological formation. The method uses a 3D wellbore friction model to estimate the coefficient of friction and effective downhole weight on bit (DWOB) from the routinely collected drilling data. An inverted rate of penetration (ROP) model uses the calculated DWOB and formation lithology constants to calculate the geomechanical properties throughout the horizontal reservoir formations such as confined compressive strength (CCS), unconfined compressive strength (UCS), Young's modulus (E), permeability, porosity and Poisson's ratio. The ROP model also takes into account drill bit information including bit type, bit wear and drill bit cutting structure along with the surface measurements of rate of penetration (ROP), flow rate and motor RPM. The routinely collected depth-based and time-based drilling data and additional data from daily drilling reports are used to calculate the geomechanical properties versus depth. This approach is compared to typical rock core and log analysis. The information obtained in the geomechanical logs can be used as design criteria to assist with improving the efficiency and effectiveness of the stimulation design which could help optimize the hydraulic fracturing process and flow potential of the well. The geomechanical logs obtained from the surface drilling data can be used as a valuable tool to optimize the completion (stimulation design) of the hydrocarbon reservoir to maximize operational net present value (NPV). A field case study is presented for a sample well in lower Eagle Ford formation. The calculated geomechanical property log is also verified with tests performed on cores in reservoir rock formations.

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NOMENCLATURE

a_1, b_1, c_1: drill bit constants

a_s, b_s, a_E, b_E: formation constants obtained from triaxial data analysis

B_x: function of drill bit properties

C_b: compressibility

D_b: diameter of bit (inches)

D_{eff}: drill bit efficiency

E: Young's Modulus (GPa)

F_t, F_b: Force or hookload at top or bottom of drill string, respectively (kN)

F_n: net normal force acting on the drill string element (kN)

G: shear elastic moduli (GPa)

h_x: hydraulic efficiency function

k: bulk modulus (GPa)

K_1, K_2, K_3, K_4: formation constants

K: empirical constant in ROP Model

K_n: mud motor speed to flow ratio (rev/min)

K_p: permeability (nD)

K_s: sliding model constant

L: longitudinal elastic moduli (GPa)

ΔL: element length of drill string

MSE: mechanical specific energy (psi)

N: rotational speed (rev/min)

ΔP: differential pressure (psi)

P_c: confining pressure (MPa)

Q: total flow (gal/min)

RO: rate of penetration (ft/hr)

SPP: stand pipe pressure (psi)

T: torque (kft-lbs)

V_c: compressional acoustic velocity (us/ft)

V_s: shear acoustic velocity (us/ft)

w: unit weight of drill string element (kN)

W: buoyed weight (kN)

W_f: bit wear function

α_t, α_b: inclination at top and bottom of drill string, respectively (degrees)

β: buoyancy factor

ρ_b: formation density (g/cm3)

μ: coefficient of friction

φ_t, φ_b: azimuth at top and bottom of drill string, respectively (degrees)

θ: dogleg angle (degrees)

ϕ: porosity (%)

CHAPTER I

INTRODUCTION

1.1 Introduction

Drilling and stimulating horizontal wellbores in shale formations has become standard practice in the US oil and gas industry. While operators have been able to optimize and effectively design and drill these wells, we as an industry have been continuously attempting to better understand and design the most effective ways to stimulate these type wellbores. Currently, the most utilized designs are driven by geometric spacing of stages and clusters that may or may not be effective in stimulating the reservoir in a way that promotes the most extraction of hydrocarbons possible. In general, the ability to more effectively design stimulation requires the use of expensive downhole logging tools and higher costs overall that aren't always economic in every well. Drilling wells faster, cheaper and safer isn't even half of the issues that the industry faces to produce wells economically but by more effectively stimulating these type of formations, the economic potential can be increased for not only one well but also for all wells in an entire field development. The use of typical drilling data can allow operators to better prepare stimulation designs that are lateral specific and can lead to a more optimized completion of each wellbore which in turn can lead to higher production and overall better economics of producing wells. The method described in this paper is provided to present an effective and economic method for using typical drilling data to generate rock strength geomechanical logs and information to assist in designing more effective and efficient stimulations in unconventional wellbores.

Continuous monitoring of rock mechanical and reservoir properties along the wellbore in unconventional horizontal wells demands convenient and efficient logging techniques. The conventional logging techniques involve laboratory core analysis and well logging operations using sonic and resistivity image logs which are not readily available for all unconventional wells mainly due to associated cost, data uncertainity and time consuming to process. Moreover, there are possible risks and concerns of trapping logging tools downhole in highly deviated and horizontal wells drilled in unconventional reservoirs. For many years, researchers and engineers have been investigating several models and techniques to obtain geomechanical property logs for the successful development of unconventional resrvoirs and stimulation design for maximum hydrocarbon production. The Artificial Intelligence and Data Mining (AI&DM) or data-driven models were developed to generate synthetic geomechanical information from the conventional logs in shale plays (Eshkalak et al., 2013). The conventional log data from a shale well were used for training and calibration during neural network model development to generate the sonic logs for other wells. These models provide better performance for the wells in proximity of the training well with actual geomechanical properties. A convenient ROP model was developed to calculate rock mechanical properties such as, confined compressive strength (CCS) and unconfined compressive strength (UCS) at each drilled depth from the routinely collected drilling data such as rate of penetration (ROP), weight on bit (WOB) and RPM (Hareland and Nygaard, 2007). In horizontal drilling, the actual downhole weight on bit differs from the measured surface WOB (obtained from on and off bottom hook load difference readings) due to the friction caused by drill string movement and wellbore geometry within the wellbore. A previously developed 3D wellbore friction torque and drag (T&D) model was used to estimate the coefficient of friction and effective downhole weight on bit (DWOB) from the surface measurements of WOB, hook load, surface applied RPM along with the wellbore survey measurements, standpipe pressure and drill string information (Fazalizadeh et al., 2010). In this article, a convenient data-driven logging technology is presented that uses the wellbore friction and inverted ROP models to calculate rock mechanical properties, such as confined compressive strength (CCS), unconfined compressive strength (UCS). In addition, the geomechanical reservoir properties which include Young's modulus, permeability, porosity and Poisson's ratio are obtained from the calculated rock strengths and lithology specific constants. The logging technology is basically composed of two software applications, D-WOB and D-ROCK as illustrated in Figure 1.

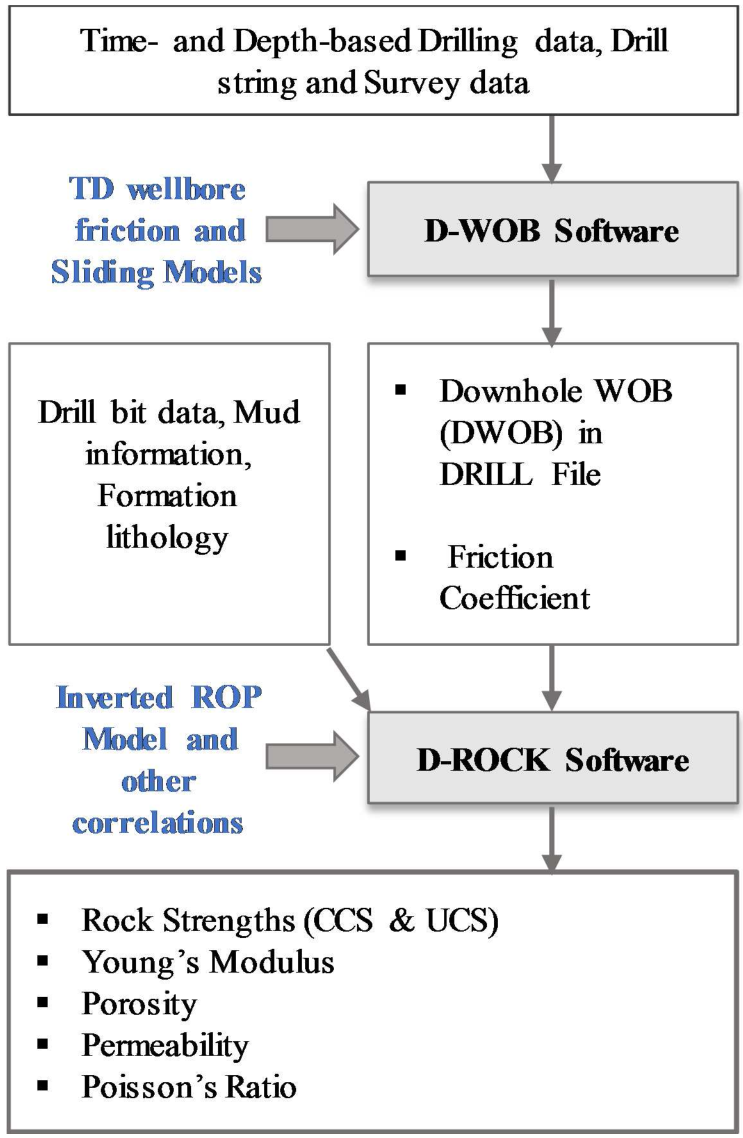


Figure 1. Overview of Data-driven Logging Technology

The routinely acquired time- and depth-based drilling data along with drill string information and survey data are the inputs D-WOB software. The outputs from the D-WOB, drill bit data, mud information and formation lithology are the inputs to the D-ROCK software in order to obtain the geomechanical property log. The mathematical models and other correlations are discussed in the following sections.

CHAPTER II

REVIEW OF LITERATURE

2.1 Geomechanics and Rock Strength Data

Geomechanical rock strength data has many purposes and applications throughout the design and execution process of drilling, stimulating and producing oil and gas wells. Geomechanical data such as rock strength values can be used for wellbore design and optimization during the drilling process. For instance, it is critical in obtaining the safe mud weight window to avoid wellbore instabilities and for planning and designing the casing program (Hareland and Nygaard, 2007). Using this type of information during drilling design and operations can assist with bit and bottom hole assembly (BHA) selection, parameter selection and optimization, and developing ROP road maps to utilize while drilling the wellbore. Rock strength has a significant impact to the drilling rate of penetration (ROP) and is therefore important information to the drilling engineer during drilling operations (Hareland and Nygaard, 2007). In wells that have geomechanical data from logs and/or cores, the surface drilling data can be utilized to correlate and confirm accuracy for other wells to be drilled in the same formations.

2.1.1 Coring and Laboratory Testing

Geomechanical data can be obtained through multiple methods but most of them are time consuming and expensive. One method to obtain geomechanical properties and data is by performing coring operations to collect intact samples of the rock from the formation and performing structural testing and analysis on the rock core in the laboratory. These type of operations are outside the scope of typical drilling operations and take extra time to complete and also have potential risks, such as downhole tool failures associated with it, which can lead to higher costs. The tools and equipment required to perform coring operations utilized to log the open wellbore are typically expensive and fragile components that have an elevated risk of failure compared to normal drilling components. Coring operations are performed while the drilling rig is on location so that the rig can be used to drill and extract the formation cores. Cores are typically taken by drilling with a core bit that houses the rock inside of a core barrel until pulled out of the hole at surface. Another option is to cut side hole cores, which requires a special coring tool to drill and cut cores to be retrieved at surface. Once cores are brought to surface, careful handling techniques must be followed to ensure the least amount of exposure and damage to the core occurs. The cores are then packaged and taken to the laboratory for an in depth analysis.

Coring analysis in the laboratory provides multiples methods for testing and calculating rock strength and geomechanical properties for the core sample. Some of these methods include: Single Stage Triaxial Compressive Tests (SST), Multi-Stage Triaxial Compressive Tests (MST), Thick Wall Cylinder Tests (TWC), and Non-Destructive Strength Tests (Strength Indicators) (Khaksar, 2009). Further information on the specific these specific tests and the testing procedures/requirements can be found in Khaksar (2009).

2.1.2 Logging Data Analysis

Geomechanical data can also be obtained with logging operations performed in the wellbore before casing is installed cemented in place to secure the wellbore. These type of operations are outside the typical scope of drilling a well and therefore can increase the cost of the wellbore. Logging tools are typically expensive and have delicate components that can increase the risk of failure while performing the operations. Service companies with wire-line equipment are typically utilized while the drilling rig is on location to run the open hole logs in vertical wells and up to certain inclinations in deviated wellbores. For horizontal wellbores, logging tools can be deployed out the end of the drill pipe with specialized tools in order to increase the ability to obtain lateral log data.

The ultimate objective of well logging is to evaluate subsurface formations by providing an indirect measurement of fluid and rock characteristics (Andrews, 2007). Well logs such as density and sonic logs are often used to assess rock strength (Khaksar, 2009). This data can be inputted into calculations to generate geomechanical data. A stress analysis obtained economically over the complete reservoir section requires continuous information format such as that available from logs. A tie between the compressional and shear acoustic travel time from logs can be related to the longitudinal and shear elastic moduli (L and G respectively) by:

$$L = \rho_b V_c^2 \; and \; G = \rho_b V_s^2 \tag{1}$$

Where ρ_b is the true formation density and V_c and V_s are the compressional and shear acoustic velocities. Ties between these two moduli can lead to a host of generally recognized mechanical properties such as Poisson's Ratio, Shear Modulus, Young's Modulus, Compressibility and Bulk Modulus. The following equations show these transforms:

$$\text{Poisson's Ratio, } \mu = \frac{.5R_v^2 - 1}{R_v^2 - 1} \text{ where } R_v = \frac{V_c}{V_s} \tag{2}$$

$$\text{Shear Modulus, } G = \rho_b V_s^2 \tag{3}$$

$$\text{Bulk Modulus, } k = \rho_b \left(\frac{1}{\Delta t_c^2} - \frac{4}{3\Delta t_s^2} \right) \tag{4}$$

$$\text{Young's Modulus, } E = 2G(1 + \mu) \tag{5}$$

$$\text{Compressibility, } C_b = \frac{1}{k} \tag{6}$$

Therefore, the quality of a reservoir's stress analysis can be related to the basic measurements ρ_b, V_s, V_s. When these three variables are available, the solution is at hand.

2.1.3 Mechanical Specific Energy

Another method to obtain geomechanical data uses Mechanical Specific Energy (MSE) to derive rock strength values for a formation. The use of MSE in the oil and gas industry has been around for over the past 5 decades, first published by R. Teale in 1965 (Teale, 1965). Drillers have used MSE to assist in the optimization of drilling performance by monitoring and mitigating downhole vibrations and increasing the rate of penetration (ROP). Completions engineers can take advantage of MSE by recognizing the relationship between it and UCS as shown below in equation (7).

$$UCS = MSE * D_{eff} \tag{7}$$

Where D_{eff} is the efficiency of the bit to transfer power of the rig to the rock (Logan, 2015). The efficiency factor typically remains somewhat constant therefore MSE can be used as a qualitative predictor of UCS (Teale, 1965).

MSE is calculated by inputting certain drilling parameters into the equation that takes into account a thrust component and a rotary component (Logan, 2015). MSE can be calculated for a horizontal wellbore using equation (8) as shown below, which includes utilization of a mud motor.

$$MSE(ksi) = 4 * \frac{WOB}{\pi D^2} + \frac{480 * (N + KnQ) * \left(\frac{Tmax}{\Delta Pmax}\right) * \frac{\Delta P}{1000}}{D^2 * ROP} \tag{8}$$

Utilizing MSE to calculate UCS can be difficult and in some cases inaccurate due to the limited number of parameters utilized in the equation and other variables that can influence drilling performance. MSE can be a good indicator of downhole vibration and drilling efficiency (Dupriest, 2005). Drillers can improve drilling performance by monitoring the MSE trends to minimize vibrations and increase ROP during drilling operations. Utilizing MSE as a trend of downhole energy required to remove rock from the wellbore can provide accurate trends for UCS values based on equation (7) (Rashidi, 2008). Even though the UCS trends from MSE can be accurate, the actual values can have a margin of error due to the unknown amount of actual vibration and inefficiency of the drill bit. More in depth testing and analysis should be performed before determining if utilizing MSE can be an accurate method of obtaining geomechanical data.

2.2 ROP Modeling and Drilling Optimization

ROP models are mathematical models, which describe how the penetration rate is affected due to; changes in operational drilling parameters, changes in the rock properties, and changes in bit types and design (Hareland and Nygaard, 2007). ROP can be directly responsive and influenced by the rock strength of the formation being drilled. Rock strength controls the depth of cut based on the amount of weight being applied to the cutting structure of the drill bit. Utilizing several drilling parameters (such as WOB, RPM, flow rate, nozzles, bit design and well diameter) in combination with drilling conditions (mud properties and pore pressure) and the resulting ROP we can generate a drillability resistance to understand what the bit must do in order to overcome the penetrating resistance of the rock. This resistance can be compared to rock strength and used to correlate both rock strength and drillability resistance for other wells in an area (Hareland and Nygaard, 2007).

2.3 Hydraulic Fracture Stimulation Design

Over the past couple of decades, hydraulic fracture design and execution has become more and more popular in regards to the production of shale-gas and shale-oil reservoirs. These type reservoirs require the formation to be hydraulically fractured to increase the low permeability that typically is associated with shale formations. There are many variables that assist the design of hydraulic fracturing treatments and operations. These include reservoir type and formation rock strength. Understanding the reservoir characteristics such as rock strength and other geomechanical properties can assist the completion engineer in designing an effective stimulation program. Methods used to acquire reservoir properties can vary and can also have different result based on the method utilized and how it was conducted. Utilizing dipole sonic logs coupled with a water injection/fall off tests can provide reservoir characteristics to aide in stimulation treatment designs (Conway and Barree, 1998). In-situ stresses in the reservoir are one of the most important parameters in hydraulic fracture geometry predictions (Conway and Barree, 1998). One way to determine in-situ stresses is to perform micro-fracs, where small volumes of fluid are injected at low rates into the formation at certain depths. These type tests can be accurately performed, but once again like other typical methods take rig time and can negatively affect the reservoir for drilling operations in certain instances. Sonic logs can also provide dynamic mechanical properties but are often discounted because it is difficult to convert these value to the static mechanical properties determined in the laboratory. Mechanical properties exhibit both size and frequency dependence and thus it is logical that different measurement techniques can provide different values (Conway and Barree, 1998).

Stimulation design based on rock strength values has the potential to be one of the most economic and accurately executed methods for effective hydraulic fracturing and placement. Utilizing surface drilling data that is available on each particular well after being drilled to generate these type of values can be the most economic option for understanding the geomechanical properties for horizontal well stimulations. These values that are specific to the lateral section of a particular well can aide in the stimulation design parameters and perforation location selection which can add significant value to the well production by increasing the effectiveness of the stimulation and production of hydrocarbons.

CHAPTER III

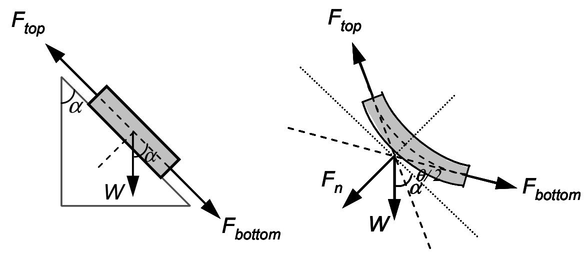
METHODOLOGY

3.1 Mathematical Models

Rock strength can be obtained from multiple methods, but the ability to accurately calculate rock strength based on surface drilling data is dependent on the quality of the data and the calculations utilized to do so. For this method, we use surface drilling data to generate downhole data to be used in typical rock strength calculations. The wellbore friction model (T&D model) is used to calculate the coefficient of friction and downhole weight on bit (DWOB) in rotary drilling mode. A sliding drilling mode model is used when the drilling is performed in a sliding mode. The inverted ROP models and other correlations are then used to generate geomechanical property logs. Utilizing these mathematical models allows rock strength and geomechanical values to be calculated for the formation along a specific lateral wellbore.

3.2 Wellbore Friction Models

The wellbore friction models (Fazalizadeh et al., 2010) were developed by considering an element of the drill string in the wellbore filled with drilling fluid and wellbore geometry. The forces considered on the drill string element are buoyed weight, axial tension, friction force and normal force perpendicular to the contact surface of the wellbore as shown in Fig. 2 (Tahmeen et al., 2014).



(a) **(b)**

Figure 2. Force Balance of a Drill String Element

Figure 2 (a) and Figure 2 (b) represent the drill string element with straight inclined section and curved section respectively. The buoyed weight of drill string element is calculated as:

$$W = \beta w \Delta L \tag{9}$$

For a straight inclined section, the force balance on a drill string element when the bit is off-bottom is:

$$F_{top} = \beta w \Delta L(\cos \alpha - \mu \sin \alpha) + F_{bot} \tag{10}$$

For a curved section in tension, the force balance on a drill string element is:

$$F_{top} = \beta w \Delta L \left[\left(\frac{sin\alpha_{top} - sin\alpha_{bot}}{\alpha_{top} - \alpha_{bot}}\right) + \mu \left(\frac{cos\alpha_{top} - cos\alpha_{bot}}{\alpha_{top} - \alpha_{bot}}\right)\right] + F_{bot}\left(e^{-\mu|\theta|}\right) \tag{11}$$

Where,

$$cos\theta = sin\alpha_{top} sin\alpha_{bot} \cos\left(\varphi_{top} - \varphi_{bot}\right) + cos\alpha_{top} cos\alpha_{bot} \tag{12}$$

For a curved section in compression, the force balance on a drill string element (Johancsik et al., 1984) is:

$$F_{top} = (\beta w \Delta L)\left[cos\left(\frac{\alpha_{top}+\alpha_{bot}}{2}\right)\right] - \mu F_n + F_{bot} \tag{13}$$

Where,

$$F_n = \left(\left[F_b\left(\varphi_{top} - \varphi_{bot}\right)\left\{sin\left(\frac{\alpha_{top}+\alpha_{bot}}{2}\right)\right\}\right]^2 + \left[\left\{F_b\left(\alpha_{top} - \alpha_{bot}\right)\right\} + \left\{(\beta w \Delta L) sin\left(\frac{\alpha_{top}+\alpha_{bot}}{2}\right)\right\}\right]^2\right)^{1/2} \tag{14}$$

The above equations are used to calculate the coefficient of friction when the drill bit is off-bottom as well as DWOB when the drill bit is on-bottom, respectively.

3.3 Inverted ROP Models and Other Correlations

The developed ROP models for PDC and Rollercone drill bits take into account the effects of bit wear, drilling parameters such as pump flow rate and RPM, and drill bit cutting structure (Hareland and Nygaard, 2007) (Rashidi et al., 2015) (Kerkar et al., 2014). Inverting and rearranging the ROP models, the rock's confined compressive strength (CCS) can be defined as follows:

$$CCS = \left[\frac{ROP}{K\ x\ DWOB^{b_1}\ x\ RPM^{c_1} x h_x x W_f x B_x}\right]^{\frac{1}{a_1}} \tag{15}$$

The unconfined compressive strength (*UCS*) and Young's modulus (*E*) are defined as,

$$UCS = \frac{CCS}{1+a_S x P_c^{bx}} \tag{16}$$

$$E = CCSxa_E x(1 + P_c)^{b_E} \tag{17}$$

Where, W_f, h_x, B_x, and a_E are lithology constants calculated using laboratory triaxial test data on reservoir core samples.

The porosity and *UCS* correlation for shale formation was obtained from various shale cores and cuttings analysis (Cedola, 2017) as:

$$\phi = k_1 x UCS^{(-k_2)} \tag{18}$$

The permeability and porosity correlation for the lower Eagle Ford shale formation was obtained from trend-line analysis as given below in equation (19) and Figure 3.

$$K_p = k_3 x \phi^{k_4} \tag{19}$$

The k_1, k_2, k_3 and k_4 values calculated for the lower Eagle Ford formation are 92.529, -0.63, 6.93 and 2.5313, respectively.

The permeability correlations were obtained from the data published by Walls (Walls, 2011).

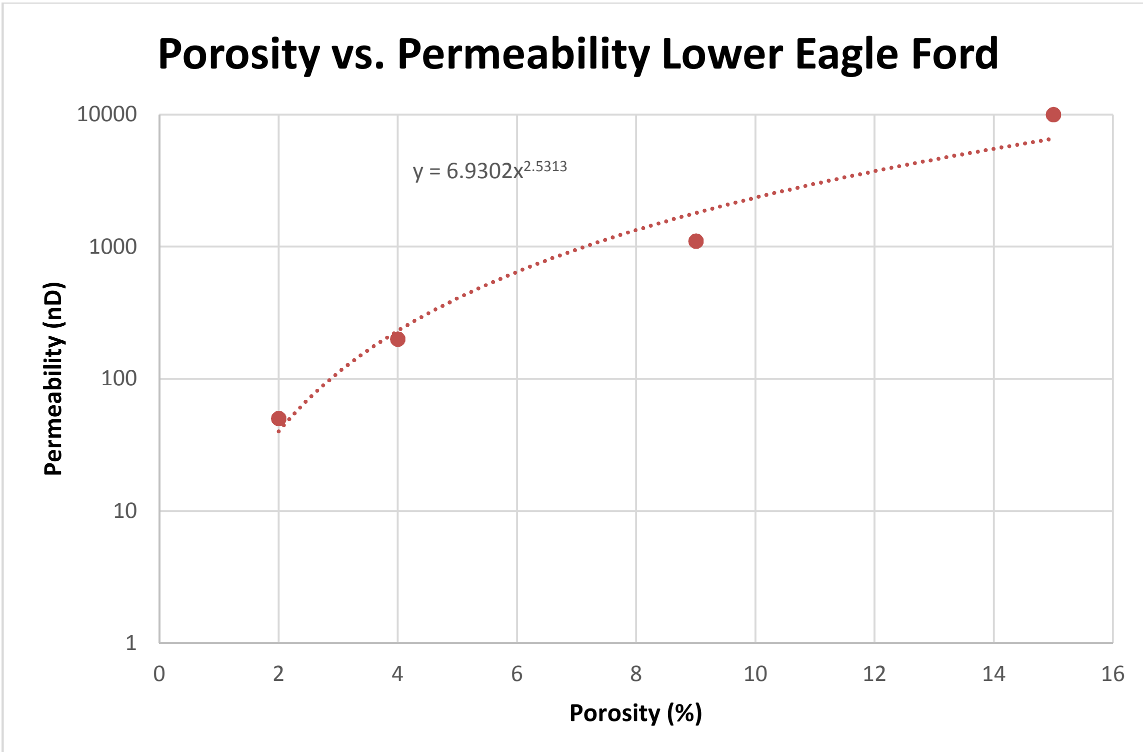


Figure 3. Porosity vs. Permeability Correlation for Lower Eagle Ford (Walls, 2011)

Equations (15) to equations (19) are used to generate a complete geomechanical property log for horizontal wells drilled in the lower Eagle Ford reservoir. It should be clarified that the software uses lithology specific constants for different reservoirs and formations within the reservoir. The constant used in equation (18) and (19) are specific for the lower Eagle Ford formation only. Different constants are used in equation (16) to (19) for different formations and reservoirs.

3.4 Inputs For Rock Strength Analysis

In this thesis, a sample field case study is presented for a horizontal well drilled from 2640m to 3460m. We utilize a software application developed specifically for utilizing surface drilling data to generate rock strength geomechanical data. The software utilizes two separate applications, D-WOB and D-Rock to generate data which can be used for multiple applications whithin the design and production of wellbores. The applications require the input of drilling data in certain formats. The quality of the data is absolutley important to the accuracy of the rock strength logs and therefore, must be reviewed and quality controlled to ensure the the input information is properly formatted. In some instances, where drilling data are unavailable or were recorded improperly, interpolation can be performed to correct for missing and/or innacurate data.

The following inputs are required for the D-WOB software:

- Drilling data: date & time, measured/hole depth, bit depth, weight on bit (WOB), hook load, ROP, RPM, stand pipe pressure (SPP), flow rate, differential pressure, etc.
- Survey data: measured depth, true vertical depth (TVD), inclination and azimuth
- Drill string configuration: drill string section lengths (bit and bottom hole assembly (BHA) components, drill pipes and heavy weight drill pipes), inner diameter, outer diameter and unit weights, etc.

- Additional data: weight of travelling block, number of lines, single sheave efficiency, mud weight, etc.

In this study, a well with doglegs up to 10 degrees per 30m and heel at around 2580m is presented for the depth interval from 2640m to 3460m in the horizontal section. The wellbore geometry information of the selected horizontal well was also used for rock strength analysis as shown in Figure 4.

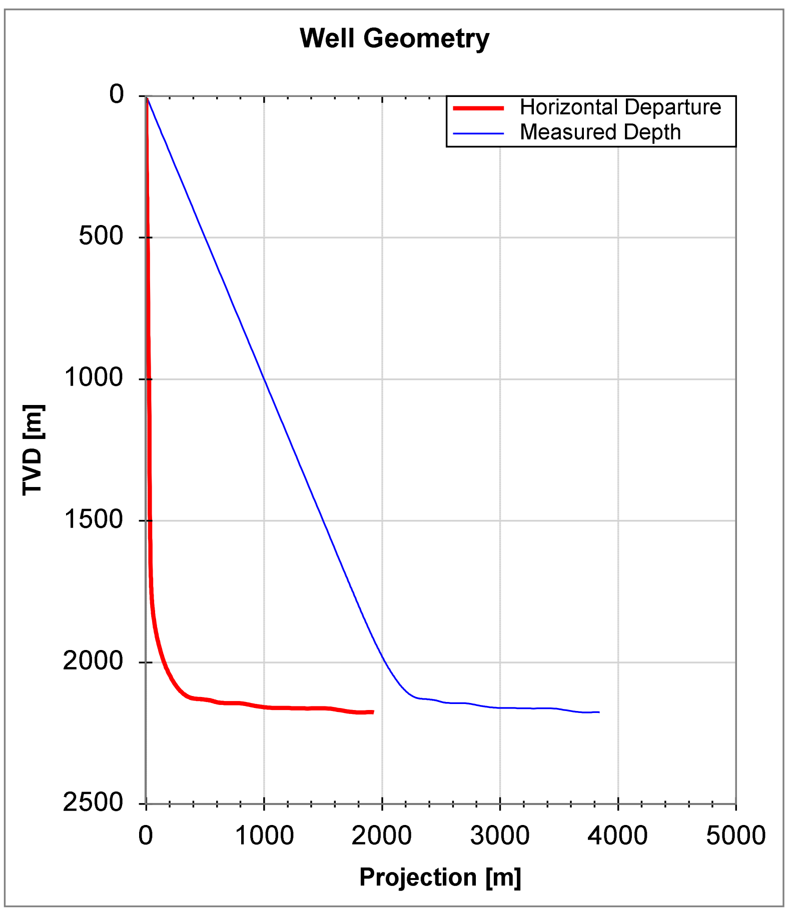


Figure 4. Well geometry of horizontal well

The following inputs are required for the D-ROCK software:

- Drill data: output data file from D-WOB including measured/hole depth, TVD, downhole weight on bit, ROP, RPM, SPP, flow rate, pore pressure, mud weight, etc.
- Drill bit data: type of drill bit (PDC or Rollercone), bit diamater, IADC code, bit wear in and wear out, number and diameter of nozzles etc.
- Mud and formation data: mud type (water or oil), mud motor constant, formation types, etc.
- Laboratory triaxial data: confining pressure, CCS, average UCS and Young's modulus

The D-WOB application is utilized to generate downhole weight-on-bit from calculated friction coefficients based on equipment and torque and drag data. After calculating the DWOB, rock strength can be calculate utilizing the D-Rock application by inputting the downhole data, bit data, and formation specific constants. Rock strength data such as confined compressive strength (CCS), unconfined compressive strength (UCS), Young's Modulus (E), Poisson's ratio, permeability, and porosity are generated and can be utilized to better understand formation integrity, pressure and characteristics along the horizontal section of the specific wellbore. This data can also be used to predict rock strength data for nearby wellbores during the planning process.

CHAPTER IV

FINDINGS AND RESULTS

4.1 Geomechanical Property Log

The routinely collected depth-based, 10 second time-based drilling data and additional data from daily drilling reports were used to calculate the downhole WOB (DWOB) required to generate the geomechanical property log.

4.2 Downhole WOB (DWOB) Calculations

The time-based off-bottom drilling data and other required inputs for D-WOB software were used to estimate coefficient of friction along the wellbore. The downhole weight on bit was calculated using the estimated friction coefficient, depth-based on-bottom drilling data and other required inputs. Figure 5 shows the difference between surface measured WOB (SWOB) and calculated DWOB using the T&D model.

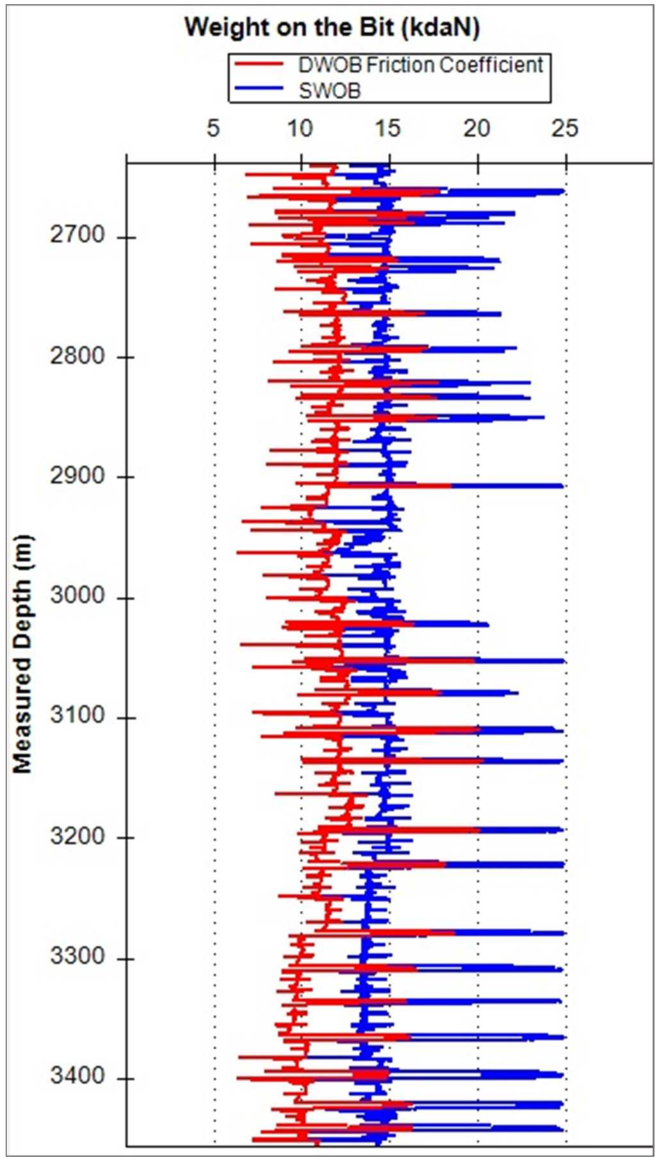


Figure 5. Downhole WOB profile from D-WOB

For the selected depth interval from 2640m to 3460m in the horizontal section, the friction coefficient was calibrated at each connection and the estimated values range from 0.09 to 0.18. The calculated effective DWOB was observed around 77.6% of the surface measured WOB (SWOB). The calculated DWOB values utilizing the T&D models were verified with the downhole weight on bit measurements obtained from the CoPilot downhole tool as shown in Figure 6.

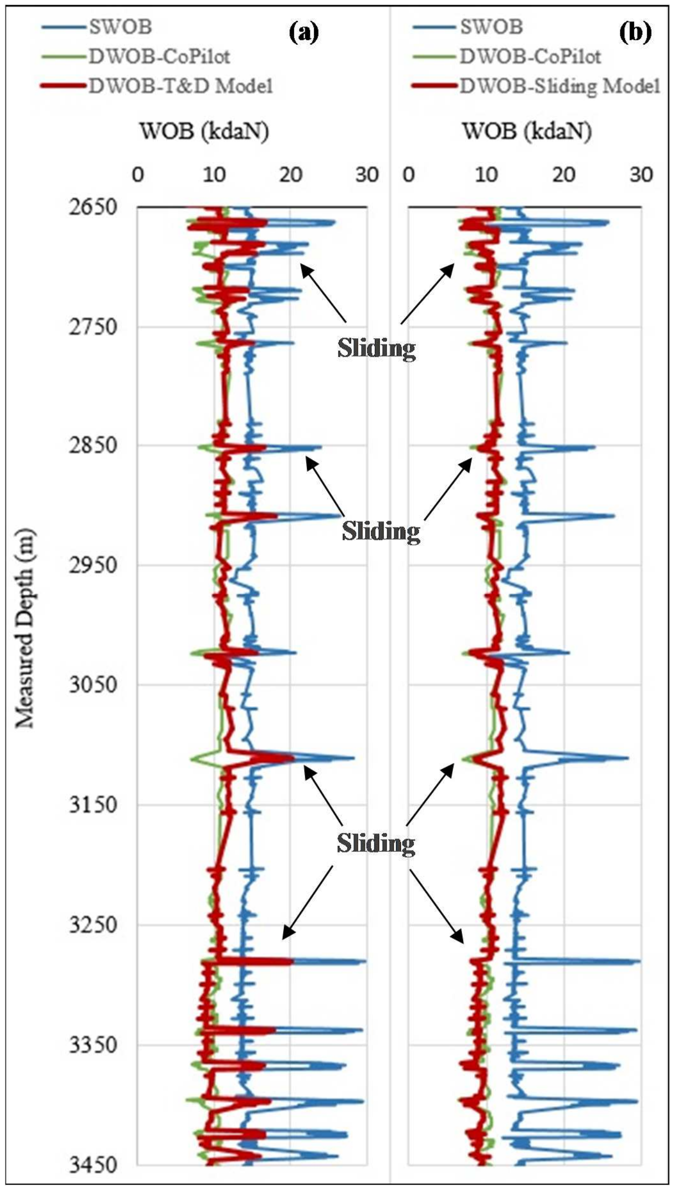


Figure 6. Comparison of calculated DWOB with the measurement from CoPilot tool

The sliding sections in Figure 6 shows higher values of surface measured WOB (blue plots). The green plot line represents the weight-on-bit measurement taken with the CoPilot downhole tool. It can be observed that there exist significant differences between the calculated DWOB using T&D models (red plot) in sliding sections and the corresponding downhole measured data as shown in Figure 6(a). The results from the T&D models show encouraging match in rotary drilling mode but not so in the sliding drilling mode.

$$DWOB_{sliding} = K_s x \frac{\Delta P}{SPP} x DWOB_{T\&D} \tag{20}$$

A sliding model was developed as a function of differential pressure across the mud motor (ΔP), DWOB at rotary mode and a sliding constant K_s (Wu and Hareland, 2015). In this article a slightly modified sliding model is used as given below:

$$DWOB_{sliding} = K_s x \Delta P \tag{21}$$

The sliding constant K_s, is obtained from the relationship of differential pressure (DP) and the corresponding T&D model based DWOB estimated during the immediate rotary drilling process. In the sliding mode, the calculated DWOB using the sliding model showed better agreement with the downhole measured WOB data as presented in Figure 6. In the sliding mode, the calculated DWOB using the sliding model showed better agreement with the downhole measured WOB data as presented in Figure 6(b).

4.3 Rock Strength Log Generation

The output from the D-WOB module was applied with other bit parameters to the PDC or Rollercone inverted ROP drill bit models used in the D-ROCK software to generate rock strength log. In this thesis, a sample horizontal well in the lower Eagle Ford is analyzed with the outputs from the well analyzed to illustrate the capabilities of the D-ROCK software. The formation constants required to obtain the geomechanical properties were calculated from the laboratory test data on lower Eagle Ford formation cores. The unconfined compressive strength (UCS) and Young's modulus logs were generated on the horizontal section utilizing calculated DWOB for sliding and rotating drilling mode depending on the operation and is shown in Figure 7.

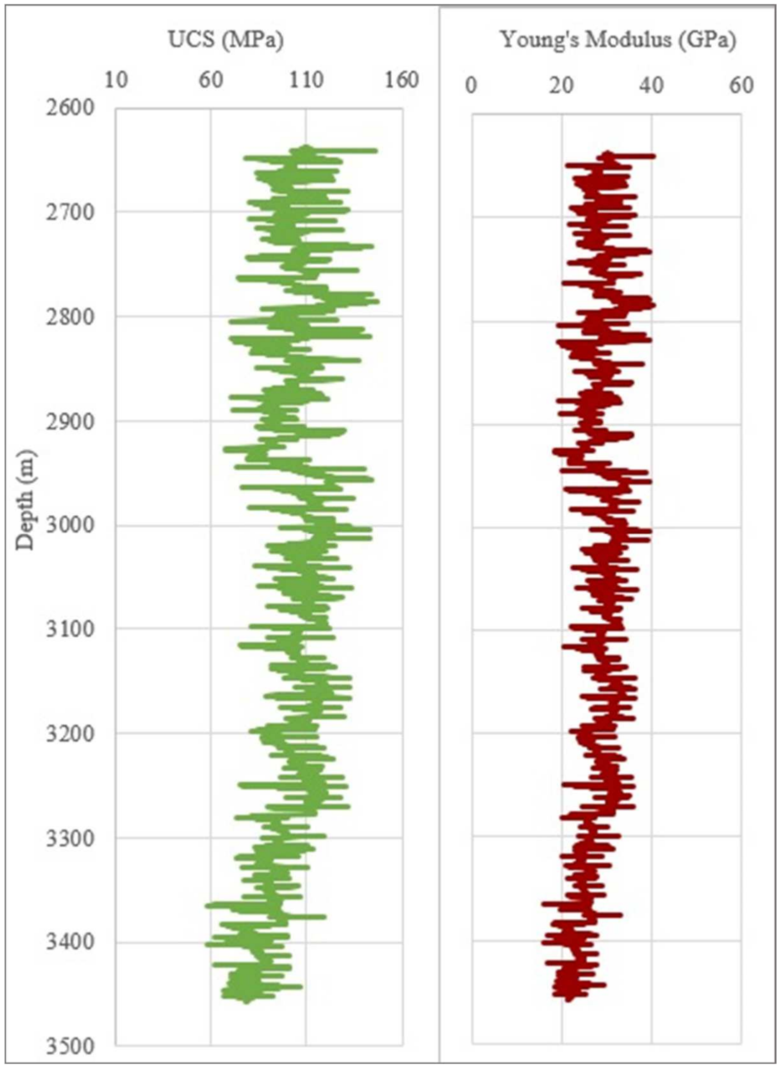


Figure 7. UCS and Young's modulus logs from D-ROCK

The decreasing UCS profile after 2900 m indicates softer formation towards the toe of the wellbore in horizontal section. In this case study, the average values of UCS and Young's modulus were found to be 102.48 MPa and 28.21 GPa, respectively. Sone reports Young modulus values for the lower Eagle Ford in the range from 25 to 34 GPa (Sone, 2012).

In this study, the geomechanical properties of Eagle Ford shale formation including porosity, permeability and Poisson's ratio were investigated to verify the D-ROCK models as shown in Eq. (18) and Eq. (19). The rock failure envelope for the lithology specific to lower Eagle Ford constants were used to calculate the rock failure angle and Poisson's ratio (Hareland and Hoberock, 1993). The regression analysis of Eq. (16) and Eq. (17) were performed to calculate the formation constants utilizing the mechanical test data for the Eagle Ford formation (Hu et al., 2014) as shown in Figure 8.

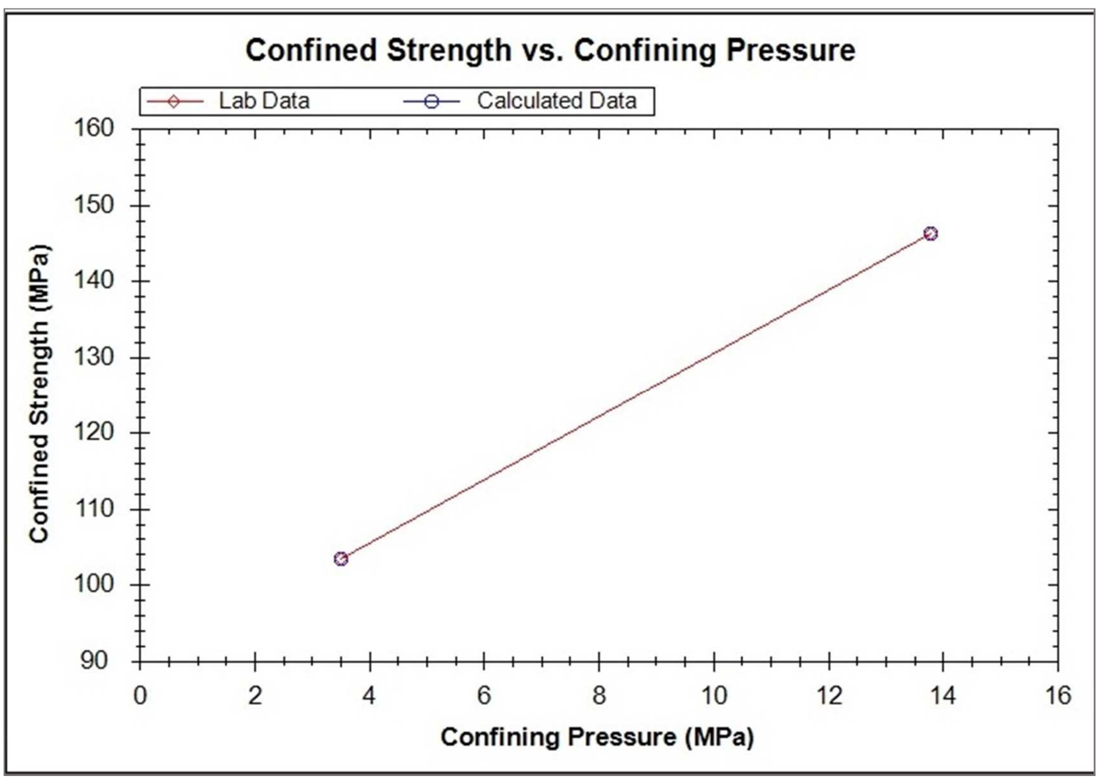


Figure 8. Laboratory data analysis to obtain constants for Eagle Ford formation

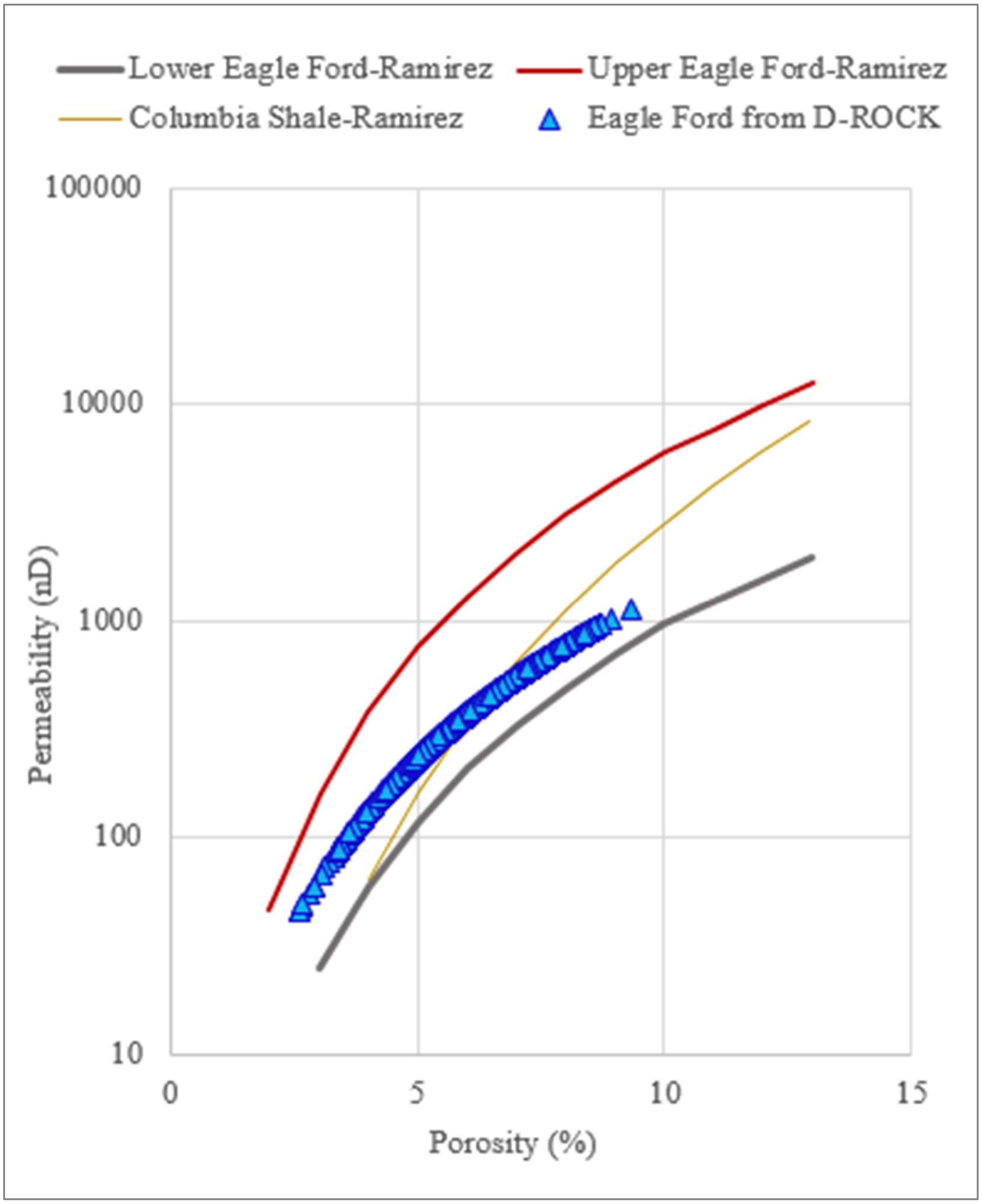


Figure 9. Porosity and permeabilty relationships for Eagle Ford formation

The porosity vs. permeability relationships obtained from the D-ROCK with data from Walls (Walls, 2011) were verified with the reported upper and lower bound trends of the Eagle Ford formation (Ramirez and Aguilera, 2016 Aguilera).

In Figure 9, the porosity vs. permeability relationship generated from the D-ROCK models indicated the location of the horizontal well near the lower Eagle Ford formation. A shale formation in Columbia is also plotted for comparison purposes.

The porosity, permeability and Poisson's ratio vs. depth for the Eagle Ford formation are also shown in Figure 10 and Figure 11, respectively.

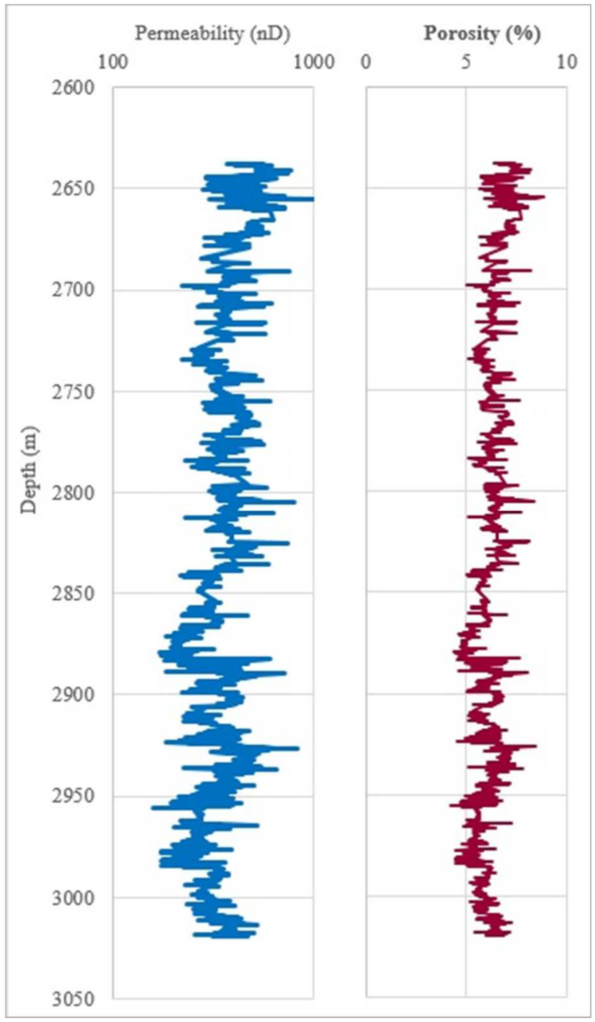


Figure 10. Porosity and permeabilty vs. depth for Eagle Ford

The higher porosity was observed at several depth intervals and indicates potential sweet spots in the shale reservoir. In future studies, the porosity model for shale formation in D-ROCK will be improved by incorporating gamma ray porosity correlations (Cedola et al., 2017) for more accurate analysis of the geomechanical properties in unconventional reservoirs.

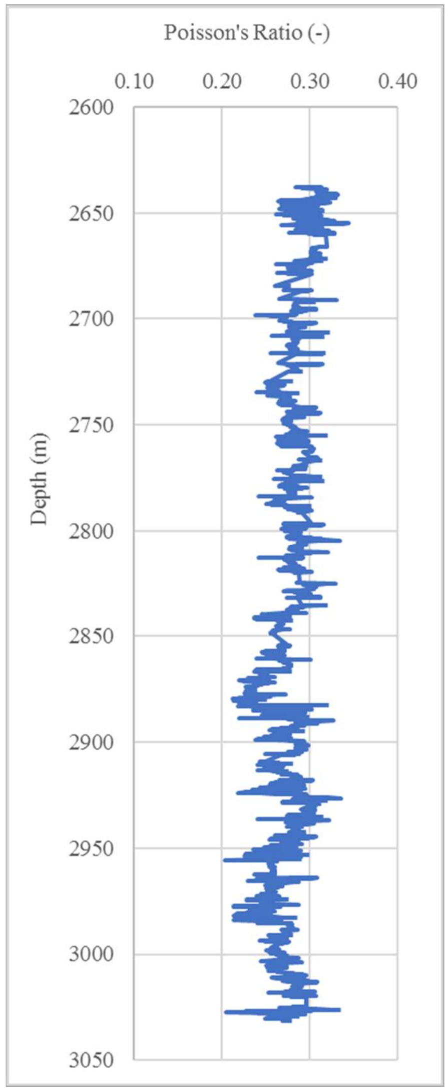


Figure 11. Poisson’s ratio vs. depth for Eagle Ford formation

The Poisson Ratio was obtained using the formation conctants used in the D-Rock software which uses the method explaind by Hareland (1993).

4.4 Stimulation Design Optimization

Utilizing the rock strength geomechanical data provides the ability to dissect the horizontal lateral section of a specific well to better understand the variation in rock strength and pressures required for hydraulic fracturing throughout the lateral wellbore. Typical stimulation design in the Lower Eagle Ford formation has been determined by some operators to be approximately 90m per stage which allows standardization for designs throughout the development of the field. The potential issues with this type of geometric design is that when stages are spaced across large sections of rock with high variations in strength, the pressures required to hydraulically fracture the formation have high variations as well. These variations in pressure can lead to isolated proppant placement within a certain section of the stage leaving other portions of the rock unfractured and without increased permeability from the inability to place proppant. This potential risk increases the probability that the wellbore isn't able to produce the maximum amount of hydrocarbons from the reservoir. Figure 12(a) provides an UCS log vs. depth showing the typical 90m stage length design. For this particular lateral section, the stimulation design utilizes 9 stages to hydraulically fracture the wellbore for production.

Below in Figure 12(b), the stimulation stage design is based on selecting stage lengths and placements with similar rock strengths. This type of design has the potential to optimize stimulation operations by grouping the sections of formation with similar rock strengths together which can potentially increase the ability to perform effective and continuous proppant placement along the horizontal lateral wellbore. By utilizing this type of method of stage design and placement, the hydraulic fracturing operations should be able to pump each stage of the job with more consistent pump pressures. This can also optimize the amount of horespower necessary to complete the frac job. For this particular lateral section, the engineerd stimulation design utilizes 13 stages based on sections with more uniform rock strengths to effectively stimulate the entire lateral section of the wellbore potentially increasing optimal production of the reservoir. Further study should be performed on actual wells with this type of stimulation design to analyze the design execution and how initial and stustained production rates compare to similar wells with the standard geometric type stimulation design.

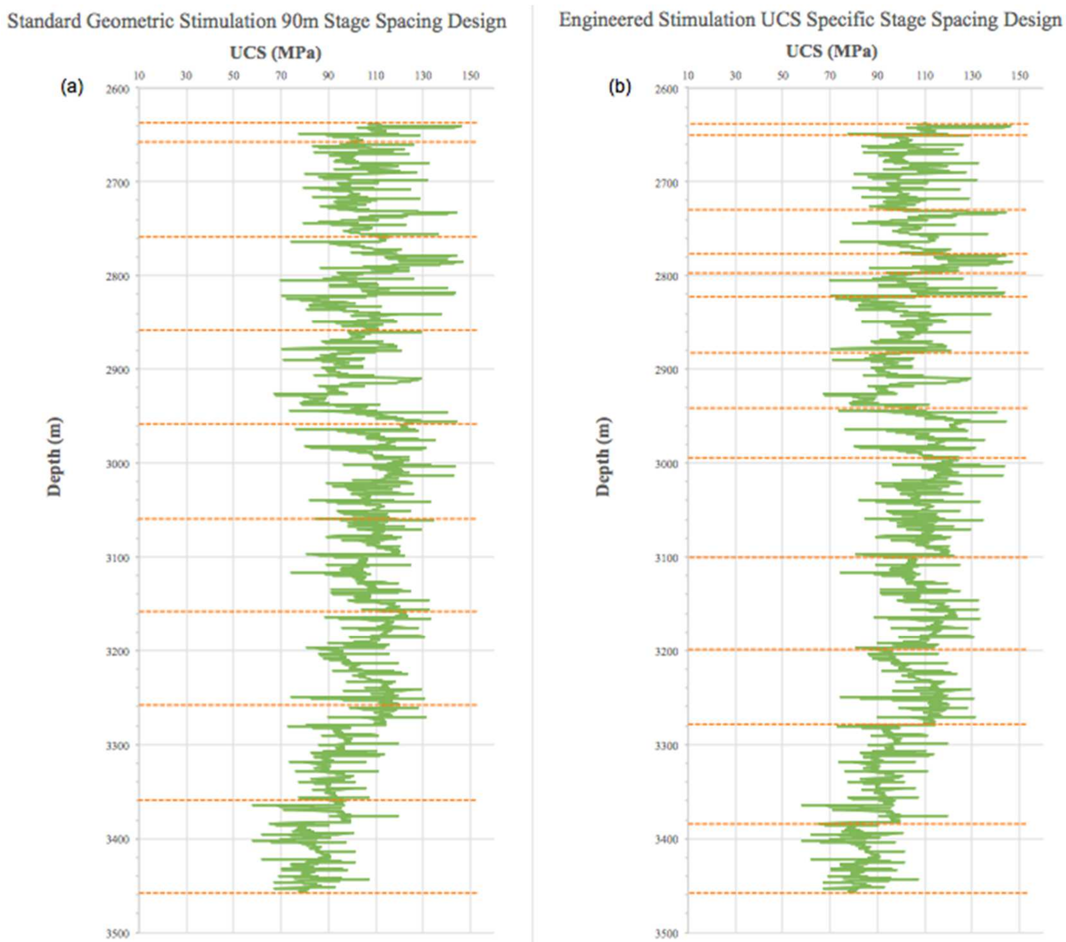


Figure 12. Geometric Vs. Engineered Stimulation Design Based on UCS

CHAPTER V

CONCLUSION

5.1 Conclusion

In this thesis, a convenient and cost effective technique was presented to obtain a complete geomechanical property log from routinely acquired drilling data in horizontal wells drilled through unconventional reservoirs in North America. The wellbore friction model and inverted ROP models were utilized to calculate effective downhole weight on bit and rock geomechanical properties, respectively. An accurate correlation was observerd between the estimated downhole weight on bit and the data measured with a downhole tool. The calculated geomechanical property log was compared to actual laboratory determined rock properties and therefore reveal the validation of this well logging technique. This validation provides confirmation that by utilizing surface drilling data, rock strength and geomechanical dat can be generated easily, accurately and cost effectively compare to other methods. This type of information can be very useful in developing better stimulation designs that promote more effective proppant placement and overall drainage of the drilled reservoir. This type of stimulation design could be measured and compared to other type designs with initial production rates and pressures, as well as, production rates over the life of the well. The information from the rock property logs can be used as inputs to map sweet spots and optimize the hydraulic fracturing process. The geomechanical property logs generated from this data-driven technology can potentially lead to optimized completion and stimulation design of shale reservoirs, using only drilling data collected during normal drilling operations at no additional cost. By utilizing this type of engineering design, operators and service companies can be more confident in the selection of equipment, proppant design, completion fluids and pumping schedules to ensure they are adequately and effectively stimulating reservoirs to their fullest potential to improve overall rate of return (ROR) and net present value (NPV) of wells within an unconventional shale play.

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VITA

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